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Grating couplers have been fabricated in thin-film PbTe waveguides on BaF_2 substrates. The grating spacings are between 1.3 and 2.1 µm, which is the appropriate range for coupling into the low order modes of a high index film (n = 5-6) with a 10.6 µm CO_2 laser. The gratings are first formed in a photoresist layer on the film using holographic or mask exposure. The pattern is then transferred to the PbTe by etching in a dilute bromic acid and bromine solution. The last step is essential for obtaining high coupling efficiencies. Due to the high index of the film, efficient coupling cannot be achieved with a low index photoresist layer alone. Coupling efficiencies are estimated to be ≈ 10%. Tuning characteristics of a number of PbTe thin-film lasers are measured. Tuning rates are typically 1.5-0.15 GHz/mA depending on diode resistance and thermal impedance. The maximum tuning range observed in a single mode was 70 GHz.

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SUMMARY

The research program under contract is directed toward determining the feasibility of an integrated optical technology in the infrared based upon IV-VI thin-films such as PbTe and PbSe grown on fluorite-structure substrates. The primary emphasis in the first quarter was the development of a theoretical understanding of waveguiding in a very high index film on a low index substrate and the application of this theory to thin-film injection lasers.

In the second quarter to be reviewed here the radiation input-coupler for the thin-film waveguide has been studied and fabricated. In keeping with the thin-film planar geometry a grating coupler has been used. The efficiency of the coupler has been measured by coupling radiation into substrate modes, thereby minimizing the effect of thin-film absorption on the signal. Experiments were performed at room and liquid nitrogen temperatures to observe waveguiding in PbTe epitaxial films.

Two experimental configurations were developed. In one case the wave reflected off the end of the film is coupled out via the input grating. In the other set-up light radiating from the end of the waveguide was collected with a lens and focused on a detector. From an estimate of the coupling efficiency of the grating the loss in the film must not exceed much more than 10 cm^{-1} or 43 dB/cm in order for the signal to be distinct from light scatter noise outside and off the surface of the film. To date no signals have been observed which can be distinctly correlated

with waveguide modes in these materials. This negative result suggests that the losses in these films are anomalously large at liquid nitrogen temperatures.

In this next quarter measurements will be made of the infrared optical absorption to test this hypothesis. The effect of film growth and post-growth heat treatment procedures on the absorption will be studied in efforts to reduce losses. The feasibility of integrating an input coupler-waveguide system with a detector will be examined as an alternative configuration to study waveguiding.

The study of PbTe diode laser sources has been extended to characterize the tunability of these devices. A number of diode lasers were fabricated to test reproducibility of the threshold conditions. Work will be continuing on laser source development in the direction of a distributed feedback laser necessary for a planar integrated local oscillator in a heterodyne receiver system.

1. INPUT GRATING COUPLERS

Coupling between external radiation sources and thin-films can be attained using prism, end-fire and grating devices. The prism coupler was first described by Tien *et al.*[1] Further theory and experiments have been reported by Tien and Ulrich[2] and by Harris and Shubert.[3] In this case the evanescent tail of the totally internally reflected light in a prism couples into the waveguide across a small gap. A tapered-film or end-fire coupler was first developed by Tien and Martin.[4] Here the input radiation is totally reflected off a tapered edge and forced into film waveguide modes in the remaining parts of the film. The grating input coupler is a periodic corrugation on a film which diffracts the incident radiation such that the diffracted light is phase matched with a waveguide mode in a film.

The choice of input coupler in the present study is dictated partly by the properties of the film and by a desire to maintain a planar thin-film configuration. In order to couple radiation into a film using a prism, the coupler must have a refractive index comparable to or greater than that of the film, which is roughly 6. There are no materials available with the size and quality that could serve as an input coupler for low-order, low-loss waveguide modes.

Since the refractive index of PbTe is so high the taper on an end-fire coupler would have to be very steep so that reflection in the taper would be at the critical angle. The control of the taper would be very difficult, and the effective length of the coupler would be small. The grating coupler, however, offers advantages: reasonably good

efficiency, precise mode conversion control, and adherence to a planar single element system geometry.

The first grating coupler was used by Dakss et al[5] in coupling 0.6 μm radiation into a glass film. A holographically exposed photoresist grating layer served as the input coupler. The coupling efficiency was measured to be around 40% from the m = 2 diffracted radiation. Grating couplers etched in GaAs films have been reported by Cheo et al[6] to couple radiation at 10.6 μm with an efficiency of 27%.

Theories of phase grating couplers have been described by Tamir et al[7], Hope[8], Harris et al[9], and Marcuse.[10] Coupling occurs when the projection of the k-vector of the incident radiation onto the surface added to that of the grating equals the propagation vector of the waveguide mode. That is,

$$\beta = \frac{2\pi}{a} q + \frac{2\pi}{\lambda_o} \sin\theta \quad ,$$

where a is the grating spacing, λ_o the free-space wavelength, q the diffraction order integer, and θ is the angle of incidence (see Fig. 1).

The discrete waveguide propagation vectors, β, are determined by solving the boundary value problem of the dielectric thin film on a substrate. The mode properties of these films have been discussed previously by two of the authors.[11] For a properly chosen grating spacing, a, there is an angle θ where the projection of the radiation on the plane of the film is phase matched with an allowed waveguide mode.

The intensity of the mode coupled wave found from theoretical analysis is dependent on the depth and shape of the grooves and the refractive index of the grating material. It is clear from arguments by Marcuse[10] that for greatest coupling efficiency the index of the grating

should match that of the guide. Matching the index of the grating with the guide requires etching the grating into the surface of the film. The depth of the grooves must be large enough for a reasonable efficiency, but not too deep as to excessively load the waveguide resulting in a poor matching with the uncorrugated regions.

Phase Grating Fabrication

The films used in the waveguide studies are 6-7 μm thick high quality epitaxial PbTe films prepared on BaF_2 substrates using techniques developed by Holloway[12] in this laboratory. The refractive index at 10.6 μm is 5.7 at room temperature and 5.9 at 77°K. The film thicknesses are determined interferometrically with an accuracy of 0.1 μm. The film refractive indices are determined from infrared transmission spectra obtained with a Perkin-Elmer Model 180 spectrophotometer. A dewar was placed in the spectrophotometer for measurements at 77°K. The index obtained from positions of the transmission maxima are accurate to a few percent. The accumulative effects of film thickness and refractive index uncertainties amount to a ± 3° uncertainty in the predicted coupling angle. From calculations of the mode propagation vector, gratings with spacings 1.8 and 2.1 μm were necessary for the 77°K and 290°K studies, respectively. These spacings enable study of the three lowest order TE and TM modes within the accessible angular tuning range.

The grating coupler was fabricated by chemically etching a periodic surface corrugation on a portion of the thin film using photolithographic masking techniques. Delineation of the grating structure can

be accomplished by exposing holographically a photoresist film on the sample. The photoresist grating can also be fabricated by conventional ultraviolet exposure through a holographic transmission mask. The latter technique produced the best results.

The transmission mask was prepared by coherent holographic exposure of photoresist spun on an aluminum film evaporated on glass. The slide is exposed to two coherent He-Cd laser beams, $\lambda = 0.44$ μm.

The photoresist developer, being an alkaline solution, acts as a weak etchant of the aluminum film. Thus, a high-quality transmission grating can be fabricated in a single resist development-metal etch process.

Figure 2 shows a top view of a grating etched into the surface of a PbTe film. Figure 3 displays a cross-sectional view. The material above the grating is an epoxy potting compound used to hold the sample during the cutting and polishing process. The groove contour, however, is essentially preserved. The films were etched in a $Br:HBr:H_2O$ (1:10:100) solution for 10 seconds in a low power ultrasonic bath, which resulted in about 0.5 μm groove depth.

Waveguiding Experiments

The waveguiding experiments were performed at room temperature and at 77°K. For the low temperature studies the sample was placed in a dewar with KCℓ windows. A 10.6 μm CO_2 laser beam was stopped down to 2 mm diameter and positioned onto the etched grating. A He-Ne laser was used to align the CO_2 laser beam with the sample and grating plane. The position of the CO_2 laser was checked using a pyroelectric detector and a UV activated thermal-sensitive plate. The position of the beam on the sample was known to within a mm.

In the first experimental arrangement employed a coupled-in waveguide mode was reflected off an etched end of the film. A schematic representation of the back-reflection is shown in Fig. 4. The back-reflected wave would be out-coupled through the input grating, deflected by a germanium beam splitter and positioned onto a liquid helium cooled copper-doped germanium detector as shown in Fig. 5. The advantage of the back-reflection configuration is that it is mode selective. It looks only at the mode generated by the input coupling process and excludes contributions from any mode conversion that may be taking place. This technique is also very convenient for the low temperature measurements as one needs only one window. The low temperature dewar was mounted on a goniometer for final alignment.

The waveguide end was delineated by using photolithographic techniques and etched in a bromine-bromic acid solution. The alignment of the 1.9 μm grating grooves with the etched edge was checked by observation under high-power metallurgraphic microscope. The alignment procedures are necessary to insure that the out-coupled beam will be very nearly along the direction of the input beam.

The sample and dewar system is mounted on a rotating table having a motor drive. With the laser beam positioned on the grating placed adjacent to the edge, the incident angle is scanned from -10° to $+25^{\circ}$, the angular extent being limited by the dewar windows. The Ge-detector voltage signal is amplified by a phase sensitive lock-in amplifier and the d.c. output is recorded on a strip-chart recorder. The transmitted beam which passes through the sample is detected with a pyroelectric sensor and recorded simultaneously.

The primary source of noise is due to scattered and reflected light from inside the dewar and from the germanium beam splitter. The noise level was measured to be at 30 dB down from the specular reflected power level off the sample at normal incidence. When the experiment is carried out at room temperature with the sample removed from the dewar the noise level is reduced to 40 dB down from the specular reflected power. However, bulk free-carrier absorption losses are excessive at room temperature necessitating the low temperature experiments.

In this experimental configuration the radiation is coupled in, reflected off the end, and coupled out using the same grating. Thus, there will be an in-coupling and an out-coupling mode conversion loss. The coupling efficiency was checked at room temperature by placing a 5 μm grating on a sample and measuring the power coupled into a substrate mode at a reduced propagation vector $\beta/k_o = 1.413$, where $k_o = 2\pi/\lambda_o$, which is in good agreement with the value of the refractive index of BaF_2 at 10.6 μm, n = 1.417.[13] The energy coupled into the substrate was of the order of 10% of the incident beam intensity. For in- and out-coupling the total conversion loss would be of the order of 20 dB. If the effective coupling length of the grating is about a mm then for a total traverse of 2 mm up to the end of the film and back, a signal to noise ratio of one is reached if the total loss in the film is 50 dB/cm or about 12 cm^{-1} assuming perfect end-reflection. That is, if the absorption and surface scattering loss is greater than 50 dB/cm, signals associated with waveguide modes would be buried in the noise. The result of experiments on a number of annealed and unannealed samples is that we have seen no back-reflected signals at or near calculated coupling angles above the ambient noise at room or at liquid nitrogen temperatures.

A second experimental configuration shown in Fig. 6 eliminates the need of coupling out through the grating a second time, yet assumes a transmission of radiation past the end of the etched-end of the film. This arrangement was employed as a complementary experiment to the one previously described. Here, the waveguided radiation that was radiated off the end of the waveguide was collected with a BaF_2 lens and focused onto a cooled Ge-detector. The scattered light noise in this case was from 30-35 dB down from the incident beam power, similar to the other experimental arrangement. Experiments at room temperature and 77°K yielded no signals that could be attributed to waveguide modes. A 10 dB loss in transmission at the end of the film waveguide is not unexpected. Thus, a conclusion similar to the first experiment concerning minimum film losses is also possible here.

Sources of Losses in PbTe

The absence of distinct signals from the waveguiding experiments implies a loss in the guide of at least 12 cm^{-1} at 77°K as a rough estimate assuming a 10 dB coupling loss through the grating coupler. The loss mechanisms that are most likely dominant are surface scattering and free-carrier absorption. No measurements have been made on surface scattering loss as this data would be very difficult to obtain on these mirror-like films. If one attributes the dominant loss at the PbTe laser threshold to surface scattering, then an upper limit results in the variance of the surface height, σ, amounting to 0.03 - 0.06 μm. This number is obtained by employing the Rayleigh scattering theory to waveguide surfaces.[2] However, at λ_o = 10.6 μm the expected surface scattering loss is less than 1 cm^{-1} using the same values for σ.

The free-carrier absorption in PbTe from intraband electron-electron scattering can be calculated using the classical expression[14]

$$\alpha_{FC} = \frac{p\, e^3 \lambda^2}{4\pi^2 n_r c^3 \epsilon_o \mu_p m_c^2} ,$$

where p is the carrier concentration, μ_p-the mobility, n_r-the refractive index, m_c-the conductivity effective mass, and ϵ_o is the permittivity of free space. Typical room temperature parameters are $\mu_p = 550\ cm^2/V \cdot sec$, $p = 6.2 \times 10^{16}\ cm^{-3}$, $\lambda = 10\ \mu m$, $n_r = 5.7$, and $m_c = 0.1\ m_o$,[15] giving $\alpha_{FC} = 11.7\ cm^{-1}$. Thus, at room temperature the calculated free-carrier absorption is too large for the observation of waveguiding. The calculated values of the free-carrier absorption agree reasonably well with experimental values observed in bulk samples.[16,17] Measurements of optical absorption at frequencies below the band gap in epitaxial films are very difficult because of the relatively low absorption and multiple interference effects from the film and substrate. An attempt was made by Piccioli[18] to measure the infrared optical absorption in PbTe films on NaCℓ. At room temperature his results agree reasonably well with the classical free-carrier absorption.

According to the classical free-carrier absorption expression, the temperature dependence of α_{FC} should follow that of the mobility. D.c. mobilities generally increase by factors of 20 or 30 at 77°K as compared with their room temperature values. A number of experiments[16,19-23] have been performed on bulk Pb-salt samples with observed reductions in the absorption of factors of only 2 to 10 at low temperatures, a significant deviation from theory. The source of this discrepancy is not understood

and no real explanations have been proposed. The extent of the absorption reduction at low temperatures in the PbTe films used here is one of the subjects to be examined in the next quarter.

Laser Sources - Tunability

Frequency tuning of the PbTe diode lasers has been studied and characterized. Frequency tuning of the laser is achieved by varying the diode current. The increase in the diode current increases the temperature by joule heating. The change in temperature alters the refractive index by changing the position of the band edge. This variation in the refractive index results in a continuous change in the laser mode frequency. Tuning rates are typically 1.5 to 0.15 GHz/mA diode current depending on the resistance and thermal impedance. The maximum tuning range we observe in a single mode was 70 GHz. The tuning ability is an important property of these lasers for their potential application as a local oscillator in a heterodyne receiver.

Figure 7a shows a laser output signal versus diode current. The radiation is detected after passing through a germanium flat of thickness of 0.9193 cm. The oscillations in the intensity are a result of multiple interference reflections within the slab. The fringes allow calibration of a tuning curve shown in Fig. 7b.

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FIGURE CAPTIONS

Fig. 1 Schematic representation of input-coupling through a surface grating.

Fig. 2 A scanning electron micrograph of a top view of a grating etched into a PbTe film. The bright areas are the top ridges.

Fig. 3 A scanning electron micrograph of a cross-sectional view of an input grating etched into PbTe.

Fig. 4 A schematic diagram of out-coupling through the input-coupler after reflection off the etched-edge of the film.

Fig. 5 A diagram of the experimental arrangement for the back-reflection experiments.

Fig. 6 A diagram of the experimental apparatus for detecting the transmitted component of the waveguide mode off the end of the film.

Fig. 7 Tuning characteristic of a thin-film PbTe injection laser. In (a) the transmitted intensity in a laser mode is plotted as a function of the diode current. The beam is first passed through a spectrometer to select a single mode and then through a Ge flat which acts as a low-finesse Fabry-Perot interferometer producing interference fringes. In (b) the fringe peak positions are plotted at constant frequency intervals, which yields the laser frequency vs the diode current.

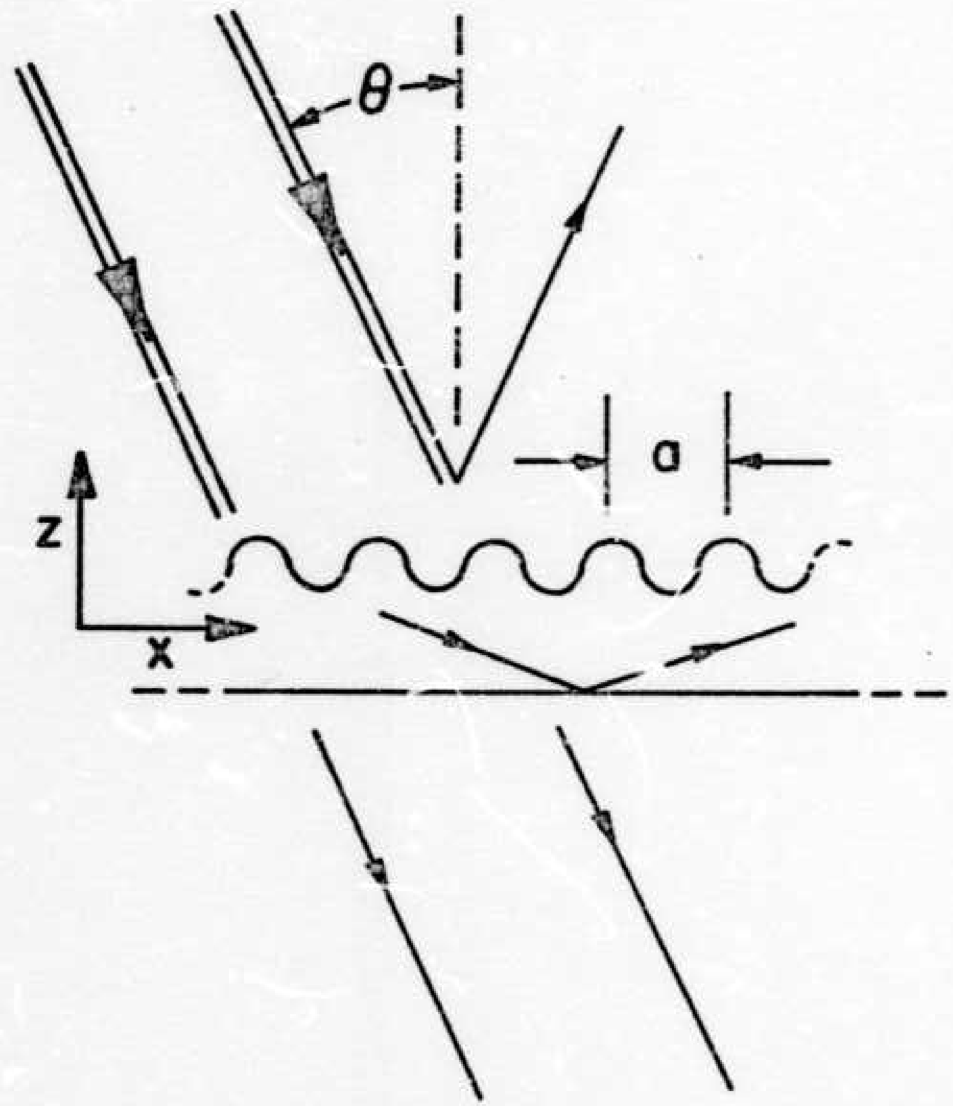


FIG. 1

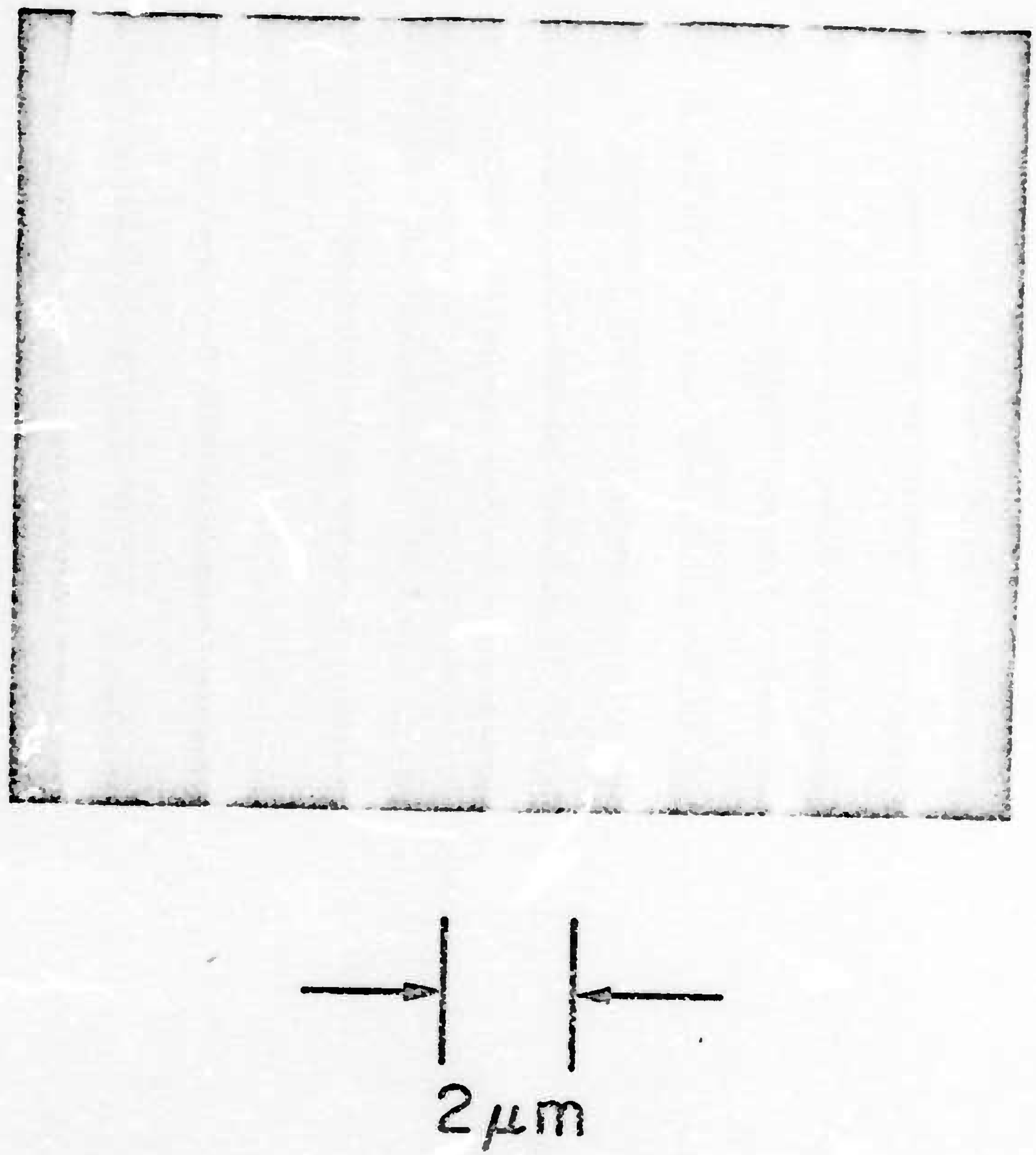


FIG.2

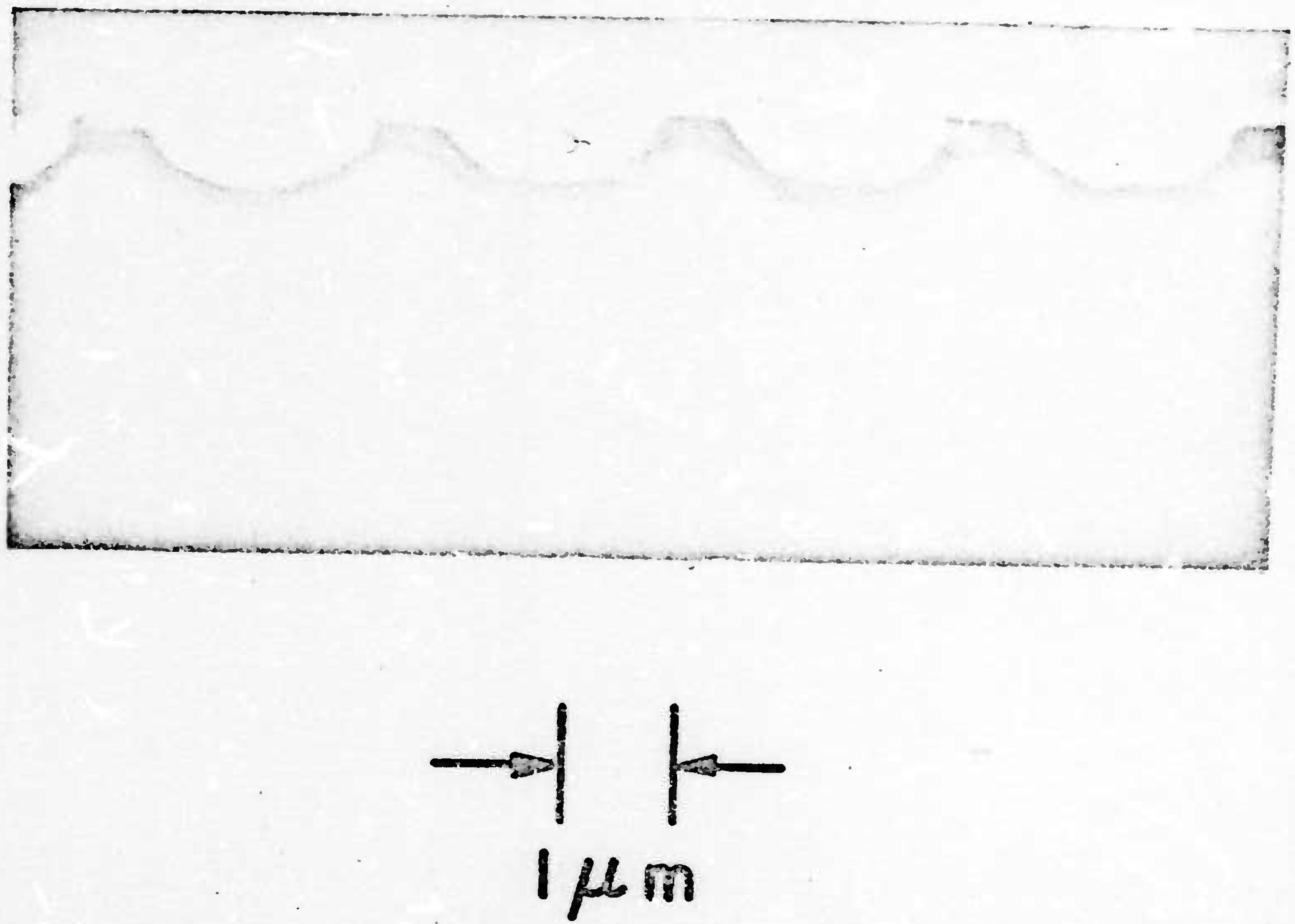


FIG. 3

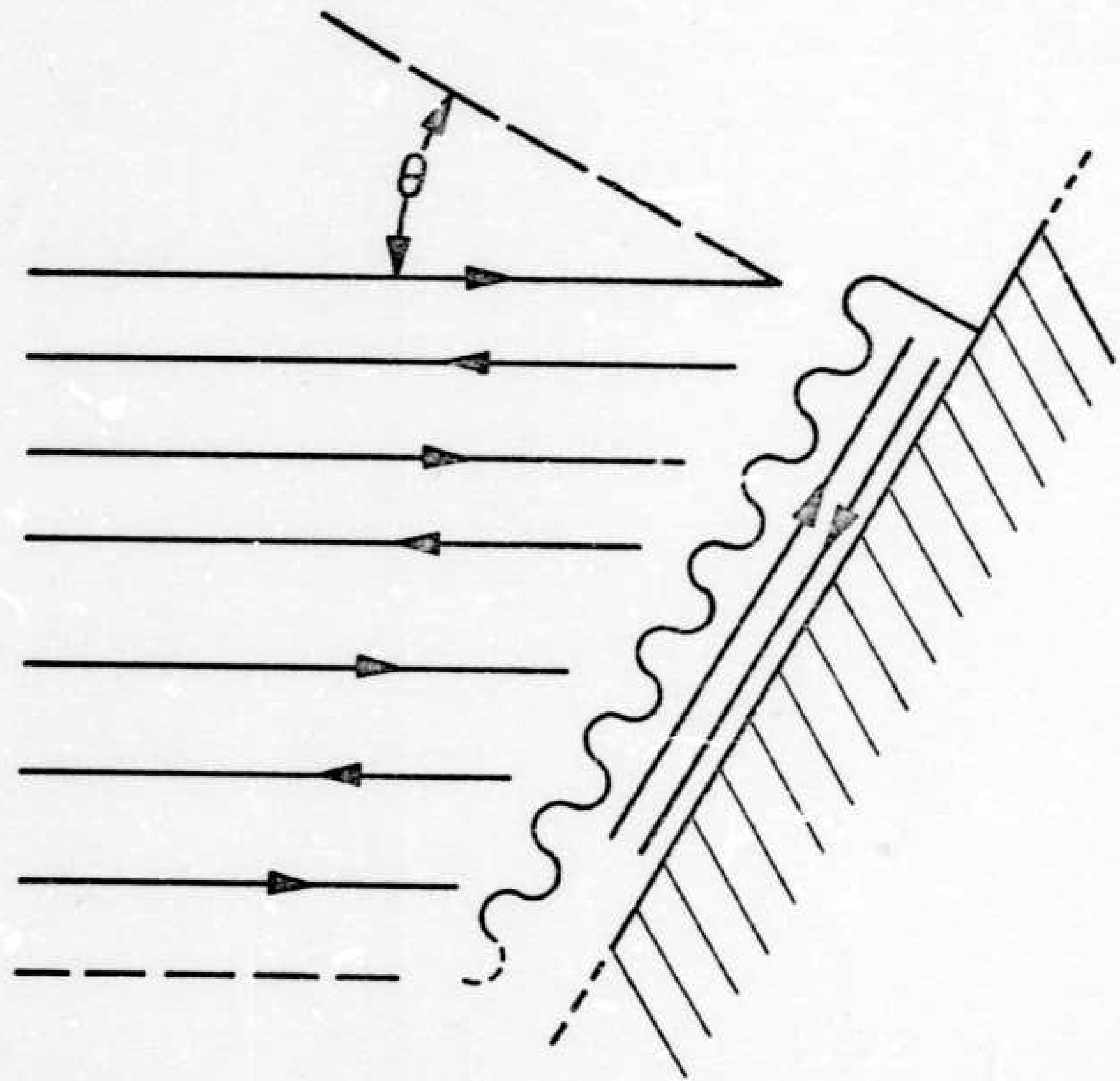


FIG. 4

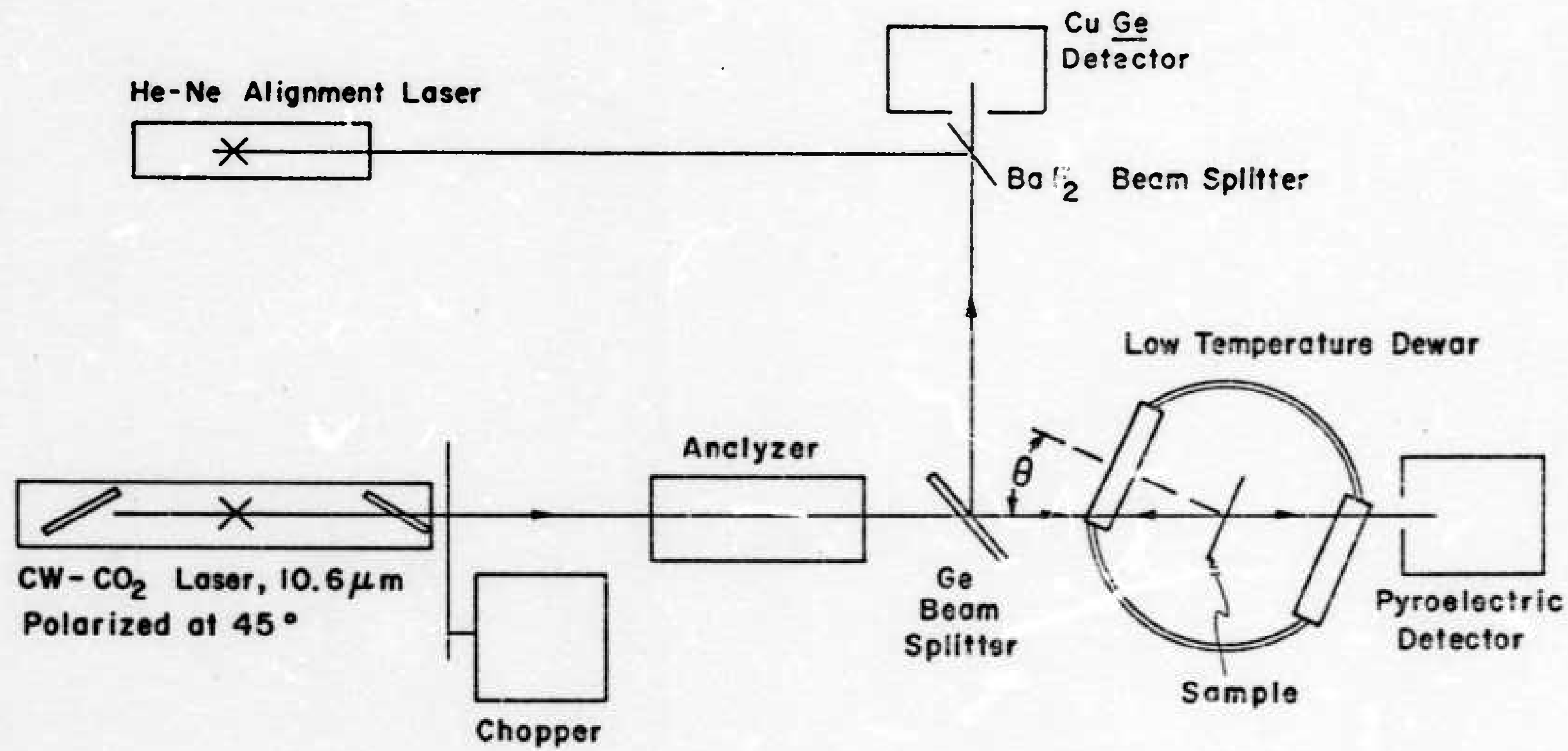

Cu Ge
Detector
He-Ne Alignment Laser
Ba F2 Beam Splitter
Low Temperature Dewar
Anclyzer
θ
CW-CO2 Laser, 10.6 μm
Polarized at 45°
Ge
Beam
Splitter
Pyroelectric
Detector
Sample
Chopper

FIG. 5

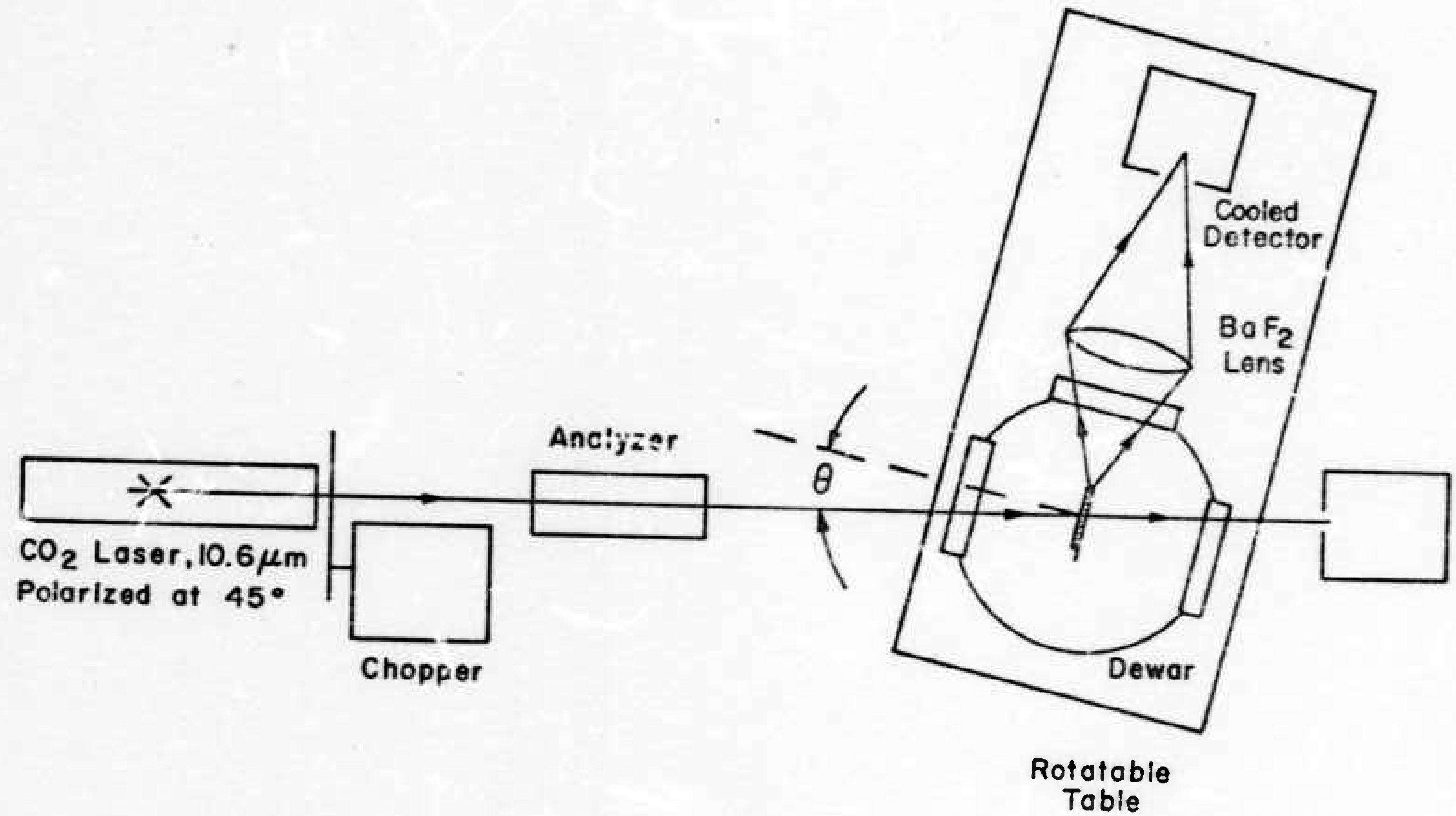
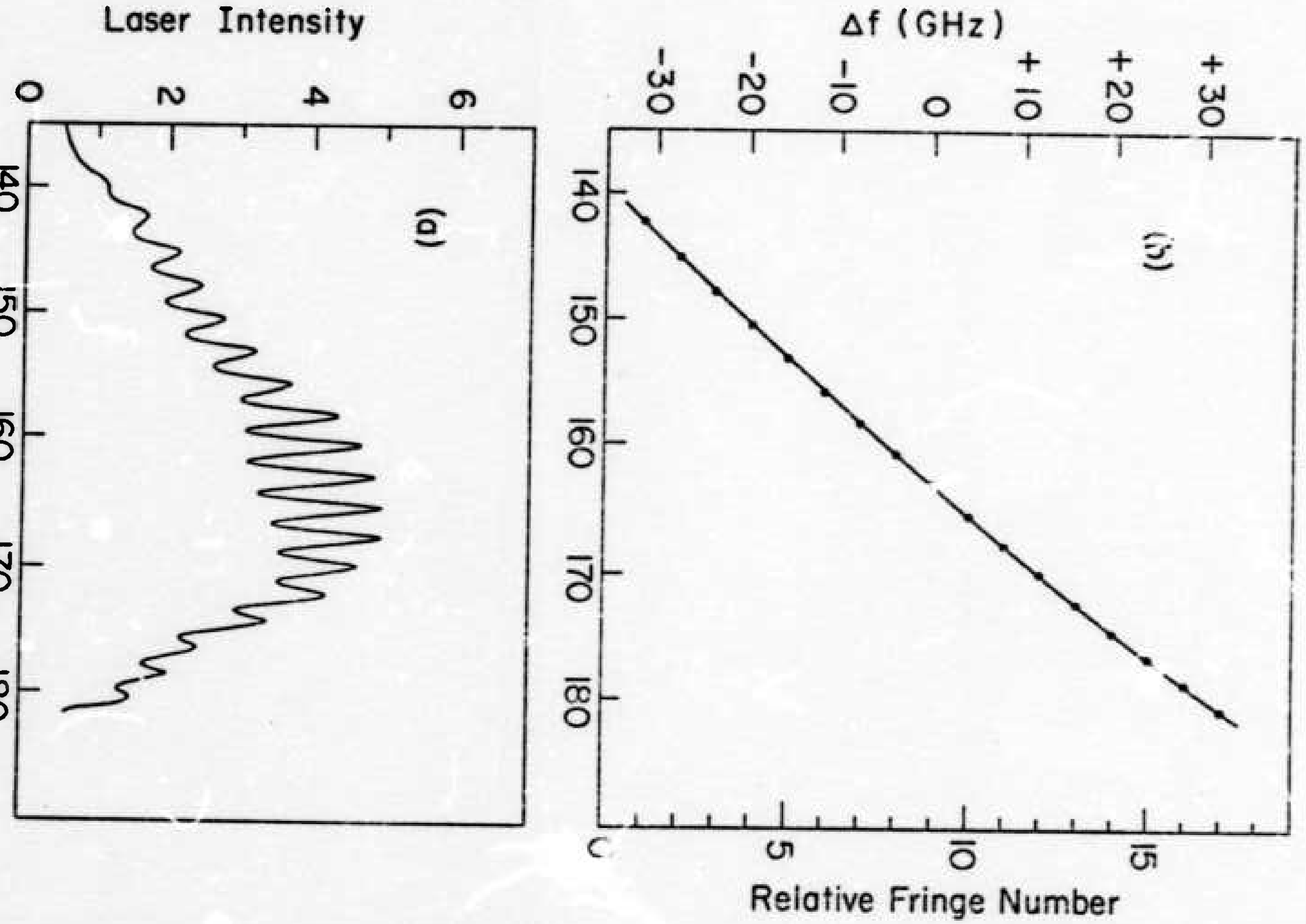

Cooled
Detector
Ba F2
Lens
Analyzer
θ
CO2 Laser, 10.6 μm
Polarized at 45°
Chopper
Dewar
Rotatable
Table

FIG. 6



(b)
Δf (GHz)
+30
+20
+10
0
-10
-20
-30
140
150
160
170
180
15
10
5
0
Relative Fringe Number
(a)
Laser Intensity
6
4
2
0
140
150
160
170
180
Diode Current (mA)

FIG. 7